

A CERAMIC LOADED POLYMER BLUMLEIN PULSER FOR COMPACT, REP-RATED PULSED POWER APPLICATIONS

Matthew T. Domonkos and Peter J. Turchi

*Air Force Research Laboratory, Directed Energy Directorate, 3550 Aberdeen Ave. SE
Kirtland AFB, NM 87117*

Jerald V. Parker, T. Chris Grabowski, Carl W. Gregg, and Chris E. Roth

*Science Application International Corporation, 2109 Air Park Rd SE
Albuquerque, NM 87106*

Kirk Slenes

*TPL, Inc., 3921 Academy Parkway North, NE
Albuquerque, NM 87109*

Abstract

The design of compact pulsed power systems involves the trade between size, pulse length, and pulse shape. A stacked Blumlein line with high dielectric constant material can deliver a voltage flattop to a matched load with an energy density similar to capacitor banks. By imbedding nano-scale titanate particles in an epoxy matrix, a composite material with a relative permittivity in the range of 30 to 60 may be realized without the drastic loss in dielectric strength associated with large area ceramics. So called ceramic loaded polymer dielectric employed in a Blumlein line facilitates the fabrication of a compact pulse forming line potentially suitable for driving loads of several tens of Ohms in the GW power range for greater than 100 ns. This paper describes the initial efforts to fabricate and test a parallel plate Blumlein incorporating ceramic loaded polymer dielectric. Two single-stage parallel plate Blumlein lines were fabricated with different ceramic loading. The lines were designed to yield a 50 ns pulse into a 6.25 Ω load. The Blumlein lines were designed to be charged to 62.5 kV, and both fabricated units held the charge voltage in static tests. A small railgap switch was fabricated for use with the Blumlein lines. A mid-plane knife-edge electrode was used to trigger the switch. The results of the tests are presented along with projections for the future development of this technology.

I. INTRODUCTION

Rep-rate and compact pulsed power generator design seeks a balance between size, robustness, and pulse quality. Many pulsed power loads are designed for a single operating voltage and operate poorly outside of their nominal envelope. Consequently, laboratory pulsed power systems are typically tuned to deliver a relatively constant voltage over a desired duration.[1,2,3] When attempting to package the pulsed power into a compact form, engineers face the challenges of maintaining the pulse shape, preventing breakdown in the compact architecture, and to a

lesser extent rejecting waste heat in high duty rep-rated systems.

In cases where the desired output voltage is greater than 100-kV, a Marx topology, a pulse transformer, or some combination of both is used to scale the voltage delivered by the power supply.[4] For compact pulse generators, the Marx topology is more commonly used since it reduces sub-system count by combining the energy storage and power scaling sub-systems.[4,5] Voltage scaling is an essential function of compact pulsed power systems since the system size is strongly driven by the storage voltage.[2] Modest pulse shaping can be accomplished with Marx banks by the inclusion or reduction of inductance between stages. Typically large rep-rate systems will incorporate a pulse forming line (PFL) to shape the pulse, whereas, compact systems may use a Marx pulse forming network (PFN) topology to address pulse shaping. While PFLs deliver very high quality voltage flat-tops to matched loads, they seldom lend themselves to compact designs. Conversely, the flexibility to tune a PFN for a load generally competes with the desire to make a compact system, and a network increases the part count. Solid dielectric pulse forming lines have the potential to store pulse energy. The PFL may also be stacked similarly to a Marx bank to facilitate voltage scaling of the output.[4,6] For common dielectrics the resulting PFL suffers from a poor energy storage density compared with other options for many compact pulsed power applications.

High dielectric constant materials may facilitate PFL design for compact pulsed power applications. Bulk ceramics exhibit an inverse relationship between their surface area and their voltage hold-off capability. As the size of a ceramic increases, the likelihood of defects large enough to enhance the electric field sufficiently to cause dielectric breakdown also increases. Therefore, despite their high dielectric constant, bulk ceramics are poor candidates for conventional pulse forming lines. TPL, Inc. has developed a composite dielectric composed of nano-scale ceramic particles suspended in an epoxy matrix. The

Report Documentation Page		Form Approved OMB No. 0704-0188
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.		
1. REPORT DATE JUN 2005	2. REPORT TYPE N/A	3. DATES COVERED -
4. TITLE AND SUBTITLE A Ceramic Loaded Polymer Blumlein Pulser For Compact, Rep-Rated Pulsed Power Applications		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER	
	5e. TASK NUMBER	
	5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Directed Energy Directorate, 3550 Aberdeen Ave. SE Kirtland AFB, NM 87117		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited		
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.		
14. ABSTRACT The design of compact pulsed power systems involves the trade between size, pulse length, and pulse shape. A stacked Blumlein line with high dielectric constant material can deliver a voltage flattop to a matched load with an energy density similar to capacitor banks. By imbedding nano-scale titanate particles in an epoxy matrix, a composite material with a relative permittivity in the range of 30 to 60 may be realized without the drastic loss in dielectric strength associated with large area ceramics. So called ceramic loaded polymer dielectric employed in a Blumlein line facilitates the fabrication of a compact pulse forming line potentially suitable for driving loads of several tens of Ohms in the GW power range for greater than 100 ns. This paper describes the initial efforts to fabricate and test a parallel plate Blumlein incorporating ceramic loaded polymer dielectric. Two single-stage parallel plate Blumlein lines were fabricated with different ceramic loading. The lines were designed to yield a 50 ns pulse into a 6.25 Ω load. The Blumlein lines were designed to be charged to 62.5 kV, and both fabricated units held the charge voltage in static tests. A small railgap switch was fabricated for use with the Blumlein lines. A mid-plane knife-edge electrode was used to trigger the switch. The results of the tests are presented along with projections for the future development of this technology.		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

resulting ceramic loaded polymer (CLP) retains a fraction of the high dielectric constant of the ceramic while enabling large scale structures to be fabricated with reasonable voltage hold-off capability.

This paper describes an effort to develop a Blumlein line using a ceramic loaded polymer dielectric. The concept is described in more detail below. Next, the initial single stage design and testing is presented, followed by a discussion of the challenges of fabricating a multi-stage line. Finally the major conclusions are summarized.

II. DESIGN CONCEPT

The Blumlein line was chosen over other pulse forming lines primarily because the output voltage of the line into a matched load is equal to the charge voltage. Pulse scaling is still required to achieve output voltages of several hundred kilovolts or higher, and a stacked Blumlein arrangement was chosen to achieve output voltages above the charge voltage. Stacking also alleviates electrostatic stress in the dielectric while the pulse energy is stored. Others have developed stacked Blumlein lines[6,7,8,9], and the primary innovations in the present work deal with the dielectric material and the stored energy density enabled by the dielectric. An eight stage variant of the Blumlein line is depicted in Figure 1 along with miniature railgap switches.

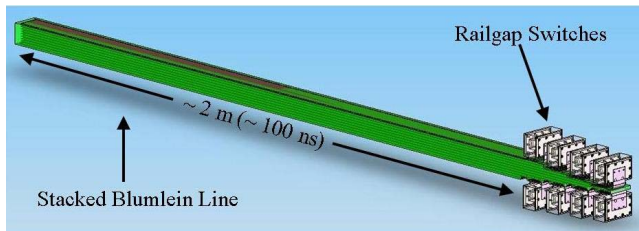


Figure 1 - Rendering of a Stacked, Parallel Plate Blumlein Line with Ceramic Loaded Polymer Dielectric

TPL has developed a unique approach for producing high energy density capacitors with complex shapes. The technology is based on a high dielectric constant nano-composite material system comprised of a polymer resin system and nano-size inorganic particles. This material allows for effective encapsulation of electrode structures. The polymer/particle slurry is infiltrated into 3-dimensional shapes, strip line geometries for example, without the assistance of solvents. The composite is then thermally cured to set the resin system. The final capacitor structure is defined by over-molding of the electrodes with the dielectric. Successful component fabrication is dependent on proper electrode alignment and material processing steps including particle dispersion, casting methods, and thermal and pressure profiles.

The performance of TPL's nano-composite dielectric comes from a combination of inorganic powders, dispersants, polymers and cure agents. The polymer system provides the forming characteristics required for encapsulation while the inorganic powders provide the increase in dielectric constant. Proper incorporation of the nano-size particles in the polymer allows for the dielectric

constant of the polymer to be increased from approximately 3 to 55. Further, the voltage stress capability of the polymer is not compromised when using the nano-size powders. The intrinsic dielectric strength of the material has been measured at 2.4 MV/cm. Provided an operational stress of 1.0 MV/cm, a material energy density in excess of 2.0 J/cc can be realized in a capacitor application. A primary goal of the current investigation is to determine the behavior of the dielectric constant of the composite material at high field stresses in pulsed operation.

A planar Blumlein geometry was chosen because it is more easily scaled to high current and high field stresses than a coaxial geometry. In addition, the ceramic loaded polymer is brittle once cured, and the natural advantage of a coaxial geometry, the ability to be coiled for compactness, is lost. The CLP can be machined, and the planar geometry simplifies the task of modification of the line for the switches.

An added benefit of the manufacturing approach is that the line can be readily encased in high dielectric strength polymer for electrical insulation. Typically transformer oil or a pressurized gas is used to insulate high-voltage pulsed power systems, although this leads to additional components and sub-systems, further confounding efforts to minimize system size. Solid insulation is preferable for compact systems since it eliminates the support sub-systems for fluid insulation.

III. SINGLE STAGE DESIGN

A single stage Blumlein line was designed and fabricated to validate the approach from both manufacturing and performance aspects before attempting to produce a multi-stage line. The line was designed for a maximum charge voltage of 62.5 kV, driving a 6.25 Ω load. The charge voltage is below the limit of common low-current laboratory power supplies. The dielectric has sufficient strength to hold off this charge voltage with margin provided voids and discontinuities can be eliminated in the manufacturing process. A stack of eight lines, as depicted in Figure 1, results in 500 kV into a 50 Ω load. The line length was intended to yield a 50 ns pulse, limited currently by the manufacturing facilities. Ultimately, lines capable of 100 ns or greater are desired. The high voltage electrode is recessed slightly from the electrodes tied to the load to minimize edge effects in the tri-plate geometry.

A small rail-gap switch, shown in Figure 2, was fabricated specifically for the parallel plate Blumlein line. The rails are approximately the same width as the line, and the switch was designed to minimized inductance. It utilizes a mid-plane knife-edge trigger electrode. The switch was originally intended to operate using pure SF₆.

Since the system consists of a specially designed switch the experimental investigation began with a characterization of the switch to ensure that the behavior of the line could be distinguished from that of the switch. The test set-up for the switch characterization is depicted in Figure 3. The energy storage and load were chosen to

closely approximate those of the single stage line. A resistive divider ensures that the knife-edge trigger electrode is kept at a potential midway between the rail electrodes. The capacitor was charged to a negative potential, and initially a self-break curve was generated for SF_6 and an Ar- SF_6 mixture. Next, the triggered behavior of the switch was examined. A +50 kV trigger pulse was sent through a peaking capacitor to the trigger electrode. It was found that using pure SF_6 caused a delay of several hundred nanoseconds in the breakdown of the gap at the voltages of interest. Consequently operation was switched to the use of the Ar- SF_6 mixture, and the breakdown was initiated simultaneously with the trigger pulse.

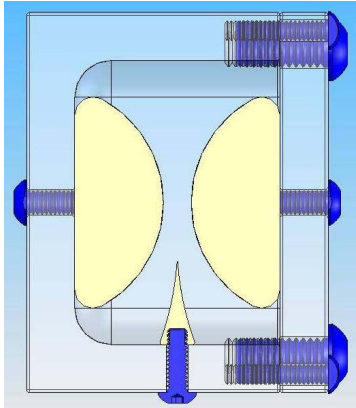


Figure 2. Side-view of the rail-gap switch showing mid-plane trigger electrode.

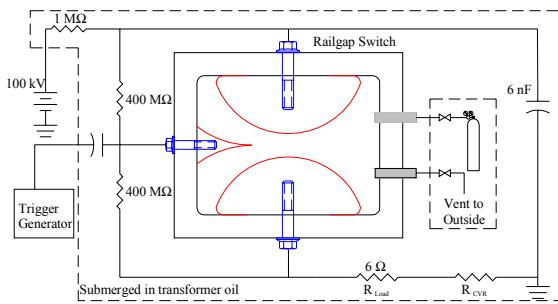


Figure 3. Test configuration for rail-gap switch characterization.

Each of the two Blumlein lines was fabricated with a slightly different concentration of the nano-scale titanate in the composite dielectric. Both of the lines have been high voltage tested to 62.5 kV with minimal machining to expose the center electrode. The lines require additional machining in order to accommodate the switch, and this is a potential source of defects in the line. A resistive load was designed to mate to the line without additional machining. The load also houses two shielded Rogowski coils and is connected in series with a current viewing resistor (CVR), as shown in Figure 4. In addition two voltage probes are used to monitor the voltage across the switch and across the load. The trigger generator and

charging power supply are configured identically to the switch test set-up. At the time of this writing, only one of the lines has undergone preliminary testing.

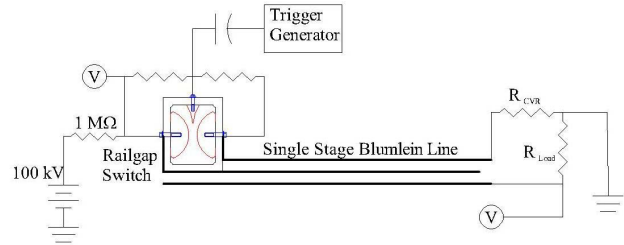


Figure 4. Electrical schematic of the Blumlein line test configuration.

IV. MULTI-STAGE DESIGN

The development of multi-stage Blumlein lines is being pursued at a measured pace, pending to test results of the single stage lines. The two major technical obstacles to the realization of a multi-stage Blumlein line with ceramic loaded polymer are the fabrication process and the switching of the line. The manufacturing techniques used to fabricate the single stage Blumlein will be extended to the fabrication of a two-stage line initially. As the number of electrodes is increased, as shown in the cross-section of an eight stage line depicted in Figure 5, the likelihood of flaws or voids increases. The field grading concept discussed earlier only complicates the manufacturing process. Two-stage lines currently under development incorporate bent and machined electrodes to accommodate the railgap switches. It is anticipated that the manufacturing hurdles will be overcome.

Switching poses a second major challenge to the operation of a stacked line. If the jitter (or even voltage decay) between the switches in the line is a significant fraction of the one way transit time of the line, then the possibility exists that the dielectric may be overstressed and breakdown. Several options exist to combat this challenge, including the use of a trigger electrode that extends closer to the center of the switch or laser triggering.[10]

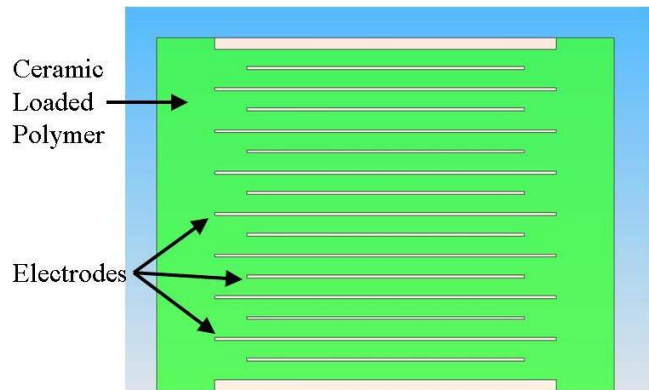


Figure 5. Cross-section of an eight stage Blumlein line showing field grading concept to minimize edge effects.

V. SUMMARY

In an effort to combine the pulse storage, scaling, and shaping functions into a single device, the development of a stacked Blumlein line with an innovative dielectric has been initiated. TPL, Inc. has developed an epoxy/ceramic composite dielectric that can be cast into complex shapes such as a parallel plate Blumlein line. Two single-stage Blumlein lines have been fabricated with the ceramic loaded polymer, and they are under test at the time of this writing. In order to test the lines, small railgap switches were also developed. The challenges of developing a multi-stage Blumlein line were also discussed, and a two stage line is currently being manufactured.

VI. REFERENCES

-
- [1] T. C. Grabowski, C. W. Gregg, D. Trujillo, *et al.*, "Refurbishment of the ETDL Rep-Rate Pulse Generator at AFRL," to be published in Proc. from the 15th IEEE International Pulsed Power Conf., Monterey, CA, 2005.
 - [2] M. Buttram, "Some Future Directions for Repetitive Pulsed Power," *IEEE Transactions on Plasma Science*, Vol. 30, No. 1, Feb. 2002, pp. 262-266.
 - [3] J. A. Casey, F. O. Arntz, M. P. J. Gaudreau, M. A. Kempkes, "Solid-State Marx Bank Modulator for the Next Linear Collider," *2004 IEEE International Power Modulator Conference*.
 - [4] W. C. Nunnally, "Critical Component Requirements for Compact Pulse Power System Architectures," *2004 IEEE International Power Modulator Conference*.
 - [5] J. R. Mayes, M. G. Mayes, and M. B. Lara, "A Compact MV Marx Generator," *2004 IEEE International Power Modulator Conference*.
 - [6] F. Davanloo, J. L. Koriath, D. L. Borovina, R. K. Krause, *et al.*, "Stacked Blumlein Pulse Generators," *1996 IEEE Power Modulator Conference*.
 - [7] R. Verma, A. Shyam, S. Chaturvedi, R. Kumar, *et al.*, "A Transmission Line Based Compact Repetitive and Portable Cascaded Blumlein Pulser," *2004 IEEE International Power Modulator Conference*.
 - [8] J. O. Rossi, M. Ueda, J. J. Barroso, "A 150kV/300A/1 μ s Coaxial Blumlein Pulser," *2003 IEEE Pulsed Power Conference*.
 - [9] M. Joler, C. G. Christodoulou, E. Schamiloglu, and J. Gaudet, "Modeling of a Compact, Portable Transmission Line for Pulsed-Power Applications," *2003 IEEE Pulsed Power Conference*.
 - [10] J. Alexander, Sandia National Laboratory, private communication, Mar. 2005.